Report to the University of Hawaii at Hilo EPSCoR Group

on

Environmental Sensor Options for the Hawaii Permanent Plot Network

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Introduction

This report was produced at the request of Dr. Jene Michaud of the University of Hawaii at Hilo EPSCoR Group and is being submitted as a project deliverable as specified in the consultant's scope of services. The analyses that led to the production of this report were performed under an informal agreement between the University and the consultant rather than a formal contract due to schedule limitations.

The objective of this phase of the project was to evaluate sensor alternatives for measurement of several environmental variables, taking into account the proposed application, approximate cost, perceived reliability and durability, sensitivity, range, accuracy, and notable advantages/disadvantages of each sensor option. The UH EPSCoR researchers provided a list of environmental parameters that will be measured with automated systems at several research plot sites located on the island of Hawaii.

Several sensor options were evaluated for this task. Technical specifications and cost information were collected from the various sensor manufacturers and distributors. Phone conversations with others who operate monitoring networks similar to those being planned by the UH EPSCoR group were extremely helpful in determining the level of perceived reliability and durability of the various sensors, as was the consultant's personal experience with several of the sensors.

The report is formatted so that each individual section addresses a single environmental variable that the client has expressed interest in measuring at one or more monitoring stations within the new Hawaii Permanent Plot Network (HIPPNet). The sensor options evaluated for each of these variables are described in a table, and recommendations and notes are made within the text of each section.

The report concludes with a brief discussion of the logistics and estimated costs of installing instrument towers at the research plots to allow for measurement of environmental parameters above the forest canopy. Manufacturer specification sheets for many of the sensors evaluated for this report are included in the Appendix.

Thorough evaluations of the most suitable sensor options are provided here for the following environmental parameters:

Soil Moisture
Soil Temperature
Air Temperature and Relative Humidity
Wind Speed and Direction
Photosynthetically Active Radiation (PAR)
Fuel Moisture
Precipitation
Net Radiation

Less thorough evaluations of the most suitable sensor options are provided here for the following environmental parameters:

Rainfall Collection
Atmospheric Deposition
Throughfall
Stemflow
Fog Drip
Stream Stage

Soil Moisture Sensors

Four (4) soil moisture sensors were evaluated for this report, two made by Delta-T out of the UK, one made by Campbell Scientific Inc (CSI) out of Logan, UT, and one made by the Onset Computer Corporation out of Pocasset, MA. Generally speaking, the evaluation included a very high-quality sensor (Delta-T thetaprobe ML2x), two high-quality sensors (Delta-T SM200 and CSI CS616-L), and a medium-quality sensor (HOBO S-SMC).

The measurement range of these sensors is very close, from 0 to around 55% volumetric water content (VWC), and should not be a limiting factor since field capacity is generally less than 40% for most soils. Except for the Delta-T ML2x, the sensors' specification accuracy are very similar, ranging from 2.5 – 3%. However the sensors' costs are significantly different (see table below). While the ML2x is substantially higher in price, it is also capable of delivering superior accuracy (+/- 1% with soil specific calibration) and will provide for a minimum accuracy in readings of 3% (with generic calibration).

Because Delta-T is recognized as the manufacturer of the highest-quality soil moisture content sensors available on the market today, consideration should be given to selecting these sensors even though their costs clearly exceed those of the competition. The CS616-L sensor is commonly used in applications similar to that being proposed at the HIPPNet sites.

Make	Model	Measurement Range	Spec. Accuracy	Approx. Cost	Cable Cost	Other Accessories
Delta T	ThetaProbe ML2x	0-60% VWC	1%	$490	5m cable incl.	ML2/INK Insertion Kit ($160)
Delta T	SM-200	0-50% VWC	3%	$276	5m cable ($23)(+$1.50/m)	SM-INRD1 Insertion Rod ($17)
CSI	CS616-L	0-50% VWC	2.5%	$150	$0.74/ft	Installation Tool 14383 ($47), Pilot Rod Tool 14384 ($47)
Onset HOBO	S-SMC	0-55% VWC	3%	$139	5m cable incl.	

Based on this evaluation, it is recommended that the CS616 or the SM-200 sensors be used for soil moisture measurements in all cases, unless very high-accuracy readings are required, in which case the recommendation would be for the ML2x probe.

Another option is the Stevens Hydra Probe. This is the same sensor that NRCS is using at 8 SCAN stations on the Big Island, and in 2 years operating these stations the Hydra Probes are working well with no reported problems. According to their soil survey guys, this probe does well in soils that experience high volumetric water content at times, like the clay soils found throughout Hawaii. Another advantage to using this sensor is that it not only measures soil moisture but also soil temperature, electrical conductivity, and dialectric permittivity. The Hydra Probe is temp.-corrected so measurements are not temp.-dependant, and they carry a 10-year warranty. I have confirmed that the Stevens Hydra Probe is compatible with the Campbell loggers, both the CR1000 and CR3000 micrologger (SDI12 inputs). Approximate cost is $350/sensor, but unfortunately Campbell does not stock these and they might have to be ordered through Stevens directly or another distributor.

Soil Temperature Sensors

Six (6) soil temperature sensors were evaluated for this report, two made by CSI, one made by Met One out of Grants Pass, OR, one by Dynamax out of Houston, TX, one each by Delta-T and Onset. Specification accuracy ranges from 0.1°C to 0.25°C while sensor cost ranges from $78 to $225.

The CSI sensors are commonly used for applications similar to that being proposed at the HIPPNet sites. The 107 temperature probe can be used in air, water, or soil. It consists of a thermistor encapsulated in an aluminum housing, designed for durability and easy installation and removal. The TCAV sensor consists of four thermocouple junctions; the probe averages two point measurements of the top 6-8 cm of soil at two locations separated by up to 1m. The TCAV sensors are typically used with one pair of probes installed at a soil depth of 2cm and the second pair at 4cm; the probes measure the soil temperature in the layer above their heat flux plates. These four measurements are then averaged to provide the soil temperature of the top 4cm of the soil profile. Since the TCAV probe is a thermocouple system, its accuracy is not specified by the manufacturer.

The CSI sensors also provide the highest level of accuracy at the least cost. For these reasons, the CSI 107 thermistor-type temperature probe and/or the TCAV averaging thermocouple probe are recommended for soil temperature measurements at the HIPPNet instrument stations. If average temperature of the top layer of soil is the desired parameter, the TCAV sensor is appropriate. If soil temperature readings at two distinct soil depths (with at least one depth > 8 cm) are desired, then the CSI 107 sensor will be suitable. It should be noted that soil temperature measurements at two different depths will require two separate 107 sensors per station.

Make	Model	Type	Spec. Accuracy	Approx. Cost	Cable Cost
CSI	107-L	Thermistor	< 0.1°C (for -24° to + 48°C)	$78	$0.38/ft
CSI ?	TCAV-L	Thermocouple, 2 depths	N/A	$165	$0.74/ft
Met One	063-1	Thermistor	0.1°C	$225	15m cable incl.
Dynamax	TM10-L10	Thermistor	0.25°C	$90	3m cable incl.
Delta T	ST2	Thermistor	0.1°C	$207	5m cable incl.
Onset HOBO	S-TMB	12-bit smart sensor	< 0.2°C	$90	2m cable incl. (+$10 for 6m cable)

Soil Heat Flux

(This paragraph is taken from an email from Tom Giabelluca and does not represent research by Mr. Rosener.) Measuring soil heat flux is necessary for energy balance studies, especially for open canopy locations. Tom Giambellucca recommends using four HFT3 soil heat flux probes and two TCAV soil temperature sensors per site for this purpose. The HFTs are installed at 8 cm. The TCAV probes both have to be installed in the upper 8 cm layer. If soil temperature is measured at two depths one needs 3 TCAVs. Also, with the added sensors, the CR1000 logger may not be adequate.

Air Temperature / Relative Humidity Sensors

Air temperature sensors and relative humidity sensors were evaluated together as these sensors are often sold as one combined probe and mounted together in the instrument array. A total of six (6) sensors were compared for air temperature & relative humidity measurements, two made by Vaisala out of Finland, one by CSI, one by Met One, one by Delta-T, and one by Onset. Several of the sensors evaluated for this category are considered to be high-quality sensors that would be adequate for the proposed application, so recommending one over another may only be a matter of personal preference.

However, with that being said, Vaisala is generally recognized as making the highest-quality relative humidity sensors available on the market. In fact, Vaisala has a very high market share (~90%) for these sensors because they have such an excellent reputation for accuracy, reliability, and durability. For this reason along with the reasonable cost, the Vaisala HMP45C is recommended for air temperature and relative humidity measurements for all monitoring stations at the HIPPNet sites. Note that the specification accuracy for temperature of the HMP45C probe is 0.2 – 0.25°C, as compared to 0.1°C for some of the other sensors evaluated. If more accurate air temperature measurements are desired, the Met One 060/083D or the Delta-T RHT2nl sensors that claim 0.1°C accuracy

Make	Model	Type	Measurement Range	Response Time (RH)	Spec. Accuracy	Approx. Cost	Cable Cost	Other Accessories
Vaisala	HMP45C-L	Platinum Resistance Thermometer (PRT), capacitive RH chip	-39.2° to + 60°C, 0.8 to 100% RH	10 sec w/ membrane filter	2% for 0-90% RH, 3% for 90-100% RH, 0.2-0.25°C for 10-30°C	$545	$0.63/ft	RM Young 10-plate gill Radiation Shield 41003-5 ($190)
Vaisala	HMT337	Warmed probe for high-humidity environments	-70° to + 180°C, 0 to 100% RH	8 sec w/ grid filter	1% for 0-90% RH, 1.7% for 90-100% RH, 0.2-0.25°C for 10-40°C	$2,290	2m cable incl. (+$160 for 5m cable)	Radiation Shield DTR502 ($580)
CSI	CS215-L	Digital humidity and temp element	-40° to + 70°C, 0 to 100% RH	< 10 sec w/ filter	2% for 0-90% RH, 4% for 0-100% RH, 0.4°C for 5-40°C	$325	$0.58/ft	RM Young 6-plate gill Radiation Shield 41303-5a ($115)
Met One	060 (temp) & 083D (RH)	Thermistor for temp, polymer capacitor for RH	-50° to + 50°C, 0 to 100% RH	< 5 sec	3% for 0-10% RH, 2% for 10-90% RH, 3% for 90-100% RH, 0.1°C	$750	$50 + $0.50/ft	073B Temp Shield ($175) or 076B Aspirated Temp Shield ($697)
Delta T	RHT2nl	Precision thermistor	-50° to + 150°C, 0 to 100% RH	< 10 sec	2% for 5-95% RH, 2.5% for < 5% RH and > 95% RH, 0.1°C for 0-70°C	$998	2m cable incl.	Solar Radiation Shield SRS2 included
Onset HOBO	S-THA	Temp/RH smart sensor	-40° to + 75°C, 0 to 100% RH	10 minutes	3% RH for 0-50°C (4% in condensing environments), 0.7°C at 25°C	$135	2m cable incl. (+$10 for 6m cable)	Solar Radiation Shield M-RSA ($90)

are recommended.

Note that a solar radiation shield must be used with all of these sensors. Costs for the recommended radiation shields are included for each sensor combination in the table below since their cost can be significant.

The Vaisala HMT337 probe is made specifically for measurements in high-humidity environments. This sensor has a warmed probe head for superior performance in condensing conditions when compared to the other probes described here. This probe is substantially more expensive than the others and draws more power due to the heating element, but it also makes more accurate humidity measurements and is suitable in high humidity environments.

Finally, if the Vaisala HMP45C combined sensor is selected for air temperature and relative humidity measurements, consideration of the Vaisala WXT510 packaged weather station should be considered for its cost-efficiency. The WXT510 combines high-quality wind (speed & direction), rainfall, barometric pressure, air temperature and relative humidity sensors all in a compact and light-weight package. Wind speed and direction are measured by an ultrasonic sensor (rather than the conventional cup and vane anemometer) and rainfall is measured by an impact sensor (rather than a tipping-bucket rain gage), so there are no moving parts in the WXT510. This allows for a low-maintenance system to collect high-quality data for standard weather variables. Power consumption will also be relatively low using this system rather than individual sensors, and the combined sensor leads only require one input channel on the data logger instead of the 4-5 channels that will be required for individual sensors. The base price for the Vaisala WXT510 is $1985.

Wind Speed & Direction Sensors

Several wind speed and direction sensor alternatives were evaluated, including both conventional cup and vane anemometers and ultrasonic sensors. Because the types of sensors and the quality of materials used to make them vary quite a bit for wind sensors, there is a lot of variability in sensor cost. All of the wind sensors evaluated combine both the wind speed and wind direction sensors into a single unit. Advantages to this approach include less equipment needed for mounting the sensors and, by design, preventing the wind speed sensor from ‘blocking’ the wind direction sensor, or vice versa.

The RM Young 05103 and 05106 (marine-grade) propeller-type anemometers with fuselage and tail wind vanes are widely used for wind speed and direction measurements in scientific research applications. They come highly recommended by many people who are experienced in the design, operation, and maintenance of weather station networks. Most wind sensors include moving parts (e.g. propeller and vane) so wear and tear is inevitable. It is not uncommon for these sensors to experience mechanical breakdowns, particularly for those constructed of less durable materials. For these reasons, the RM Young 05106 combination sensor is recommended for use if a conventional anemometer is desired for wind speed and direction measurements. If this sensor is considered too expensive, the Met One 034B anemometer could be selected instead. This sensor is slightly less accurate but less than half the cost.

Make	Model	Type	Measurement Range	Spec. Accuracy	Approx. Cost	Cable Cost	Starting Threshold
RM Young	05106-L (marine-grade)	Propeller-type anemometer	0-60 m/s, 0-360°	0.3 m/s, 3% for direction	$1,100	$0.63/ft	1.1 m/s
Met One	034B	3-cup anemometer and vane	0-50 m/s, 0-360°	0.11 m/s for < 10.1 m/s, 1.1% for > 10.1 m/s, 4% for direction	$495	$70 for 10m	0.4 m/s
Delta T	AN3 & WD1	3-cup anemometer and vane	0.15-75 m/s, 0-359°	1%, 0.3° +/- 2° in winds > 5 m/s	$3,003	3m cable incl.	0.15 m/s
Vaisala	WINDCAP WMT50	Ultrasonic	0-60 m/s, 0-360°	0.3 m/s or 3% for 0-35 m/s, 5% for 35-60 m/s, 3° for direction	$995	2m cable - $60, 10m cable - $100	None
Vaisala	WS425	Ultrasonic	0-65 m/s, 0-360°	0.135 m/s or 3% for 0-65 m/s, 2° for direction	$1700 ($2045 heated)	10m cable - $100	None
Vaisala	WM30	3-cup anemometer and vane	0.5-60 m/s, 0-360°	0.3 m/s for < 10 m/s, < 2% for > 10 m/s, < 3° for direction	???	???	0.4 m/s
Onset HOBO	S-WCA	Wind speed/direction smart sensor	0-44 m/s, 0-358°	0.5 m/s for < 17 m/s, 3% for 17-30 m/s, 4% for 30-44 m/s, 5° for direction	$499	3m cable incl.	< 0.5 m/s

Another consideration is the starting threshold for cup (or propeller) and vane-type sensors. Because these sensors rely on the movement of the propeller and/or wind vane to measure wind speed and direction, respectively, a certain amount of wind speed is required to initially overcome the internal friction of the sensor components. The Met One 034B has a specification starting threshold of 0.4 m/s, and the RM Young 05106 has a starting threshold of 1.1 m/s. If a starting threshold is determined to be unacceptable for the proposed application, ultrasonic wind sensors should be considered instead of conventional anemometers.

Vaisala is the recommended vendor for ultrasonic wind sensor alternatives. Their wind sensor line includes the WS425, a research-grade ultrasonic wind speed and direction sensor, and the WINDCAP WMT50, an ultrasonic sensor that is comparable in cost to the high-end conventional wind sensors. The WMT50 is included as part of the Vaisala WXT510 weather transmitter that was described in the previous section. Of course the lack of a starting threshold is a considerable advantage for ultrasonic sensors when compared to conventional anemometers, but there are other advantages that should be considered as well, especially the lack of moving parts that makes them virtually maintenance-free.

Re-calibration of the ultrasonic sensors is not required, however re-calibration is very important for conventional anemometers to ensure that they attain the highest possible accuracy. The calibration frequency is typically 1-2 years, and it should be noted that field-calibration may not be possible, meaning that wind sensors may have to be sent to the manufacturer or a wind tunnel facility for re-calibration. This can result in data gaps unless spare sensors are available for temporary replacement.

Precipitation Sensors

Several rain gages were evaluated for their potential use at the HIPPNet instrument stations. These included one made by Texas Electronics out of Dallas, TX, three made by Hydrological Services out of Australia, and one each made by Met One, Vaisala, and Onset. All of these sensors are tipping-bucket rain gages whose accuracy varies depending on construction materials, with the exception of the Vaisala gage which relies on an impact sensor and a correlation between impact force and raindrop size to determine the amount of rainfall it measures.

The Texas Electronics TR-525 tipping-bucket rain gage is commonly used for rainfall measurement at weather stations. However, its suitability for hydrological research is questionable due to its limitations in measuring high intensity rainfall. While this may not be an issue in some areas, it should be an important consideration in Hawaii where high rainfall intensities are relatively frequent. For accurate measurements of the full range of rainfall rates, including burst intensity, the Hydrological Services tipping-bucket rain gages are recommended. This recommendation is based in large part on the author's personal experiences with different rain gages.

The TB5 rain gage can be fitted with the siphon assembly from the more expensive TB3 gage to achieve the same level of accuracy at significant cost savings. The selection of this sensor should result in accuracy of 2% for high intensity rainfall up to 20 in/hr and even better accuracy for lower rainfall rates.

Make	Model	Type	Spec. Accuracy	Approx. Cost	Cable Cost	Notes / Accessories
Texas Electronics	TR-525I	8" dia. tipping-bucket	1% for up to 1"/hr, -2.5% for 1-2"/hr, -3.5% for 2-3"/hr	$385	$0.36/ft	No accuracy stated for intensities > 3"/hr
Hydrological Services	TB5	8" dia. tipping-bucket	4% for 1-20"/hr	$495	10m cable incl.	Field calibration device ($495), Leveling baseplate ($105)
Hydrological Services	TB5 w/ TB3 siphon	8" dia. tipping-bucket	2% for 1-20"/hr	$537	10m cable incl.	Field calibration device ($495), Leveling baseplate ($105)
Hydrological Services	TB3	8" dia. tipping-bucket	2% for 1-20"/hr	$850	10m cable incl.	Field calibration device ($495), Leveling baseplate
Met One	370	8" dia. tipping-bucket	0.5% for up to 0.5"/hr, 1% for 1-3"/hr	$572	$50 for 50ft.	No accuracy stated for intensities > 3"/hr
Vaisala	RAINCAP WXT510	Impact sensor	5%	N/A	N/A	Not available as individual sensor, only in multiprobe
Onset HOBO	S-RGA	6" dia. tipping-bucket	1% for up to 1"/hr	$389	2m cable incl. (+$10 for 6m cable)	Measurement range 0-5"/hr

addition to table: TR525 has a calibration device for $220.

Finally, Vaisala offers an alternative method for measuring precipitation with its RAINCAP sensor that is included in the WXT510 weather station package. This sensor does not rely on buckets tipping with a known volume of rainwater, but instead detects the impacts of individual raindrops on a sensor plate. The signals resulting from impact detection are proportional to raindrop volume so the signals can be converted directly to accumulated rainfall.

While this type of precipitation sensor is not expected to perform well for very low (misting rain) or very high (burst) rainfall intensities, it does have some advantages over the traditional tipping-bucket rain gages since there are no moving parts and clogging/flooding of the sensor and evaporation losses are eliminated. The RAINCAP sensor cannot be purchased as an individual sensor but only as part of the WXT510 weather station package (base price $1985).

P.S.: Regarding the decision to go with the Texas Electronics rain gages instead of the Hydrological Services gages, I am not really comfortable with this, but ultimately it's not my decision. I have talked to many people about this including Tom Giambelluca, Kevein Kodama at NWS, Barry Hill at USGS, and Steve Burges at U-W who has done performance studies on various rain gages and is the one suggesting the potential undercatch problem with siphoning gages. I found out that USGS is still using some older tipping bucket rain gages but they are transitioning over to all Hydrological Services TB3 gages from here on out. At some stations they are collecting rain discharged from the tipping-bucket gages in accumulation cans and in all cases the catch difference has been < 5%. Kevin told me the NWS is currently considering switching over to the HS – TB3gages too (most of their tipping buckets are the old Handar gages). NWS is also moving away from tipping-buckets and towards weighing gages at some of their stations (airports). My understanding is that the siphon assembly in the Hydrological Services gages is what allows for accurate measurements at high rainfall intensities. If what Steve Burges is suggesting is true, they may undercatch at lower rainfall intensities due to the siphon. However we should also be considering the fact that a non-siphoning ('straight-through') tipping-bucket rain gage will undercatch during high intensity rainfall, by as much as 15%. So either way, there will be undercatch at times. It's probably a decision that should be made based on the relative importance of high quality data for frequent, low- intensity rain vs. episodic, high-intensity rain.

Net Radiation Sensors

Four sensor options were evaluated for measurement of net solar radiation, including one made by Detla-T, one by Met One, one by Kipp & Zonen out of Bohemia, NY, and one by Radiation & Energy Balance Systems (REBS) out of Seattle, WA. Because the specifications for some of these sensors do not include expected measurement sensitivity or accuracy, and most of the sensors are similar in cost, it is difficult to recommend one over another. All of the sensors evaluated seem suitable for the proposed application, so sensor cost may be a deciding factor. The Met One 097 Net Radiometer has a slightly lower cost than the Kipp & Zonen NR-Lite and REBS Q7.1 sensors, and its reliability and durability is perceived to be comparable, so it would be a good choice for measurement of net radiation in the instrument arrays. However, the Kipp & Zonen and REBS sensors are also good choices if the slightly higher cost is considered insignificant.

Make	Model	Spectral Response	Response Time	Sensitivity	Spec. Accuracy	Approx. Cost	Cable Cost	Accessories
Delta T	NR2	0.25-60 µm	not specified	not specified	5% @ 20°C	$2,282	7m cable incl.	Support arm ($188)
Met One	097	0.25-60 µm	10.5 sec	75 mV/kW m^2	not specified	$1,025	$40 for 40ft.	Comes with supporting arm & mounting plate
Kipp & Zonen	NR-LITE	0-100 µm	20 sec	10 µV/W m^2	not specified	$1,630	$0.36/ft	Mounting kit required (14264, $180)
Kipp & Zonen	CNR1	0.3-2.8 µm	18 sec	7-15 µV/W m^2	10% for daily total	$6,195	25m cable incl.	Mounting kit required (14264, $180)
Radiation & Energy Balance Systems	Q7.1	0.25-60 µm	time constant ~ 30 sec	not specified	not specified	$1,250	$0.29/ft	Mounting kit required (CM210, $42)

The Kipp & Zonen CNR1 is a research-grade net radiometer that consists of two pairs of pyranometer/pyrgeometer sensors, one pair upward-facing and the other downward-facing. The pyranometers and pyrgeometers measure short-wave and far infrared radiation, respectively, and an RTD is included to measure the instrument's internal temperature. More data is collected from the CNR1 when compared to the other sensors evaluated here, but the trade-offs are its much higher cost and data logger input channel requirements (6 differential or 4 single-ended and 2 differential analog channels vs. 1 differential or analog channel for the NR-LITE sensor).

PAR Sensors

Make	Model	Type	Measurement Range	Spec. Accuracy	Approx. Cost	Cable Cost	Accessories
Li-Cor	LI-190SZ	Quantum sensor	400-700 nm	5%	$340	3m cable incl. (+$15 for 15m cable)	leveling/mounting fixture ($47), mounting stand ($31)
Delta T	QS2	Si photodiode	400-700 nm	5%	$965	5m cable incl.	Support arm ($188)
Delta T	ES2	Si photodiode	400-1050 nm	5%	$637	5m cable incl.	Support arm ($188)
Met One	096	Si solar cell	400-1100 nm	< 5%	$425	$40 for 40ft.	Leveling/mounting fixture incl.

Four sensors were evaluated for measurement of Photo-synthetically Active Radiation (PAR). PAR, also called Photosynthetic Photon Flux Density (PPFD), is defined as the number of photons in the 400 – 700 nm waveband incident per unit time on a unit surface.

Because LI-COR Biosciences, out of Lincoln, NE, is considered a leader in the development of light sensors and has a reputation for reliable and durable products, the

LI-190SZ is recommended for measurement of PAR in the instrument arrays. It should be noted that the sensor cost shown in the table here ($340) is for purchase directly from the manufacturer. CSI sells the same sensor for $550. The Met One 096 pyranometer is also considered to be a good choice for PAR measurements for the proposed application, and it is comparable in price.

Fuel Moisture Sensor

Only one fuel moisture sensor option was identified in the research for this analysis. It was developed by CSI, in conjunction with the USFS, and is fabricated to USFS specifications. The CS505 Fuel Moisture Sensor measures the moisture content of a ½”-diameter, 20”-long Ponderosa Pine dowel and produces a +/- 2.5 V square wave. The wave’s frequency is read through an analog or pulse channel on the datalogger and converted to a moisture content value (%) using a quadratic calibration. This sensor’s operating range is 0 – 70% moisture content, and its specification accuracy is 1% rms at 0 – 10% MC and 2.4% rms at 30 – 40% MC. Because no other sensor options were identified for measurement of fuel moisture, the CS505 is recommended for use in the instrument arrays.

Throughfall Measurement

Throughfall is defined as rainfall that makes it through the forest canopy to the forest floor either with (drip) or without (straight through) contact with the canopy. Stemflow, or the portion of rainfall that is intercepted by the canopy and eventually makes it to the forest floor by flowing down plant/tree stems, is not considered to be part of throughfall. Throughfall is measured in many ways; examples include stationary and roving precipitation funnels, troughs, and plastic sheet gages. Unfortunately, there are drawbacks to every approach to measuring throughfall. A significant problem with these measurements is the difficulty in achieving representative area averages. For example, in using funnels for throughfall measurement, studies have shown that accuracy of 20% is possible with a few gages but several hundred gages were required to achieve 5% accuracy.

Using troughs for throughfall collection has some advantages over using funnels. Because of their length, troughs can provide more representative throughfall measurements, and fewer troughs than funnels are needed to achieve the desired level of accuracy. Disadvantages to using troughs instead of funnels include the tendency of raindrops to splash out of the trough and larger adhesive losses due to the larger receiving surface area.

Plastic sheet gages can provide good average throughfall data, but they have their problems too. One concern is the likelihood of holes eventually developing in the sheet due to extended use or falling tree branches. Adhesive losses can also be significant. Long-term diversion of rainfall from large areas in the forest for plastic sheet gages will eventually stress the forest plants. For these reasons, along with the difficulties in constructing and maintaining plastic sheet throughfall gages, their use is discouraged at the HIPPNet sites.

The collection devices for all of the methods described above typically divert throughfall to a tipping-bucket rain gage for measurement. An alternative is the use of load-cell based systems where a weighing gage with minimal wind losses is used for gross precipitation measurement and weighing troughs are used for throughfall measurements.

Dr. Tom Giambelluca, from the University of Hawaii at Manoa, has successfully used gages that utilize troughs for collection and a large tipping-bucket gage for measurement of throughfall. Dr. Ali Fares, also from the University of Hawaii at Manoa, is currently using a similar system for throughfall measurement at plot sites located on leeward Oahu. It is recommended that one of these instrument designs be used at the HIPPNet plot sites if throughfall measurements are desired for the HIPPNet research programs.

Stemflow Measurement

Stemflow is the portion of gross rainfall that is intercepted by the forest canopy and eventually makes it to the forest floor by flowing down plant/tree stems. This component of the water budget is typically measured by installing collars on tree stems that divert stemflow to a tipping-bucket rain gage for measurement. Dr. Tom Giambelluca, from the University of Hawaii at Manoa, has used this sensor design to measure stemflow. It is recommended that the same or a similar instrument design be utilized for stemflow measurements at the HIPPNet sites.

Fog Drip Measurement

In many areas of the world, the magnitude of fog drip in relation to the other components of the water budget can be considered insignificant, and its measurement is therefore not important (or even possible). However, fog drip has been shown to be a significant component of the water balance in some areas, including the cloud forests of the Hawaiian Islands.

Much research has been performed to develop measurement techniques for fog drip. Notably, University of Hawaii at Manoa Professor Tom Giambelluca has been a leading contributor in this effort. The fog drip component has been notoriously difficult to measure directly for obvious reasons, so researchers often resort to indirect measurements of fog drip by making direct measurements of the other components of the water balance equation and mathematically solving for the single unknown variable.

As expected, the sensor research performed for this analysis did not identify any commercially available instruments for direct measurement of fog drip. If fog drip must be determined for the HIPPNet plots, it is recommended that the indirect measurement (i.e. mathematical derivation) approach be utilized. HIPPNet researchers should also discuss other options for determining the magnitude and spatial/temporal variability of fog drip with Dr. Tom Giambelluca, Geography professor at the University of Hawaii at Manoa.

Rainfall Collection for Chemical Analysis

The standard protocol for collecting rain samples for chemical analysis was developed for use in the NADP (National Atmospheric Deposition Program). This protocol is considered a standard method, and it should be followed closely if data produced through the sampling & analysis program are intended to be published.

Concentrations of dissolved substances in precipitation are generally low, and there is a high possibility of bias influencing the analysis results in sample collection and analysis for chemical constituents. Common sources of bias include sample contamination during handling, losses to the sample container, chemical/physical/biological changes in the sample, and variations in collection and analysis procedures. For these reasons, a strong and effective quality assurance (QA) and quality control (QC) program is necessary to ensure that meaningful data is obtained from a rainfall chemistry sampling program (http://nadp.sws.uiuc.edu/).

As such, the NADP has developed well-defined QA programs with well-defined QC criteria. These criteria apply to the siting of collection systems, sampling/analysis protocols, and processing/reporting of data. The automatic sensing wet/dry precipitation collectors used for the NADP are manufactured by Aerochem Metrics. There are likely other instruments from other manufacturers that could be substituted as an equivalent to the Aerochem Metrics samplers, but none were identified for this report. Please note that rain collectors for stable isotope analysis are different than those used for wet/dry atmospheric deposition. Several precipitation isotope collection instrument designs are described by the USGS at http://water.usgs.gov/nrp/proj.bib/hawaii/precip_methods.htm.

Stream Stage Sensors

Several methods are used for automated measurement of stream stage (height). These methods generally include the use of submersible pressure transducers, gas bubblers, or acoustic sensors. Pressure transducers (PTs) are commonly used because of they are relatively inexpensive and easy to install, operate and maintain. The transducer measures the pressure head at the point in the water column where the sensor is mounted, and this pressure value is converted to water depth above the sensor (pressure head is directly related to water depth by the unit weight of water).

Because PTs must be submerged in stream water in order to measure stream stage and they are susceptible to damage by bedload or debris in the stream channel during high flow events, they are usually installed inside a stilling well in or near the stream channel. The stilling well is intended to protect the sensor and to create a still water environment more conducive to steady stage readings. The average cost of a quality PT is about $700; however the costs of other hardware needed for the gaging station can be significant. Depending on site conditions, the installation of the stilling well and gage house (if necessary) can be much more expensive than cost of the sensor itself.

Gas bubblers consist of the bubbler unit, typically located in a gage house or other enclosure some distance away from the stream, and an orifice line that connects the bubbler unit to the water column in the stream channel. The measurement principle is the same as that described above, except the measurement device is located at the bubbler unit away from the stream channel. The bubbler unit constantly pushes gas bubbles through the pressurized orifice line into the stream water. The pressure required to force gas bubbles into the stream water is converted to stream stage using the same mathematical relationships described for pressure transducers. The stream stage values are then recorded to the data logger.

A significant advantage to using bubblers versus submersible pressure transducers is the location of the sensor itself. For a submerged pressure transducer, the probe is located in or near the stream channel and therefore is vulnerable to damage or loss during peak flow event. For a bubbler, the sensor is typically located in an enclosure far enough from the stream that it cannot be damaged during high flow conditions; if anything is damaged it will be the orifice line which can be easily replaced at minimal cost. Measurement range is similar for both PTs and bubblers, generally 0-35 ft. Also, both types of probes can provide a similar level of accuracy, generally about 0.007 ft. However the cost of a bubbler is typically two to three times the cost of a PT.

Finally, acoustic sensors are used to measure stream stage in some cases where it is undesirable to mount any portion of the measurement system below the high water elevation. These systems rely on the acoustic response of radio (RaDAR) waves transmitted from a sensor mounted above the stream channel to determine the stream stage value. These types of sensors are often used in cases where structures are already on site for sensor mounting (e.g. stage measurement at bridges). Because of they are generally more costly than the other sensor options described above, their use for measuring stream stage at the HIPPNet sites is discouraged.

Site conditions should be carefully considered before choosing the location for stream stage measurements and for choosing the measuring system. Stream stage values by themselves are not particularly useful in many cases, but stage values can be converted to stream discharge values through the use of a rating curve. The rating is typically developed for a stream gaging station by making repeated measurements of stream stage and stream discharge over a range of flow conditions. All stream discharge measurements require the use of a velocity meter (cost $5000 approximately), and for high flow measurements in large stream and rivers, other expensive equipment may be required at the gaging station (e.g. cableway).

As few as 10 or as many as 20 measurements are required to develop an accurate rating curve, and it should be noted that ratings change over time as stream channel geometry changes. So continual maintenance of the rating via discharge measurements is needed to ensure accurate flow data is produced from the gaging station. A more efficient way to measure stream discharge is to install a control structure in the stream channel such as a weir of flume. If the structure is constructed to specific dimensions for which known hydraulic relationships are available, measured stage values can be directly converted to discharge values using hydraulic formulae instead of developing a rating curve through repeated flow measurements. Much less work is required to install, operate, and maintain these types of gages over the long term. However, the increased initial cost of installing a large physical structure in the streambed and the potentially difficult permitting process involved should also be considered in deciding if control structures are a suitable method for streamflow measurement at the HIPPNet instrument sites.

Towers for Sensor Mounts Above Forest Canopy

Research was performed to determine the rough costs (+/- 25%) of installing instrument towers at some of the HIPPNet field sites. Tower-mounted sensors may be desirable for comparisons of environmental variables above and below forest canopy. For this analysis, forest canopy height was assumed to be 40-50 feet. Based on this assumption, instrument towers approximately 60 feet high would be required.

Pre-fabricated aluminum towers (typically transported in modular 10-foot lengths) are available from several manufacturers, notably Universal Towers out of Michigan and Rohn Industries out of Illinois. These towers are typically used for radio and cellular transmission applications, but they are also used for mounting weather sensors high above ground level in many cases.

The cost of a new tower assembly, including the aluminum frame segments and steel base, is approximately $100/10ft. length (or $10/ft.) plus $100 for the baseplate. So for a

60-foot tower, the assembly cost will likely be about \$700. The cost of guy wires and other hardware needed for tower installation would also be roughly \$700. With freight costs added to the combined costs of the tower materials, the total cost is likely in the range of \$2500 – 3000.

However it is very important to note that by far the largest expense in building towers like the one described above is installing the anchors, both for the tower base and for the guy wires. A 60-foot high guyed tower would required 2 guy lines (at 2 different heights) on 3 sides of the tower (6 guys lines, 6 guy line anchors). Guy lines would be anchored at a distance of 48 feet from the tower base. Of course anchoring requirements need to be determined based on local wind load and soil conditions, but in rough numbers, a 2ft^2 x 3ft deep base anchor and six (6) 2ft.x2ft.x2ft. guy line anchors will be required for a 60-foot tower.

Since the cost of constructing the anchors (typically from concrete) will be highly dependent on the ease of access to the tower sites, and the cost of installing anchors in-place usually far exceeds the cumulative hardware cost for the tower assembly, it is extremely difficult to generate even rough estimates for the full cost of tower installations. With that said, the full cost of a single 60-foot tower installation may be as little as \$10,000 (for tower sites within range of a concrete pump truck, ~200 feet) or as high as \$60,000 (for remote tower sites requiring all materials to be air-lifted in by helicopter). A much more accurate estimate could easily be prepared if the proposed tower locations in relation to access roads was known.

Incident Solar Radiation Sensors (Pyranometers)

Solar, or short-wave, radiation is a significant driver of large scale atmospheric motion, and for this reason it has an important place in meteorology. Four sensors were evaluated for measurement of incident solar radiation including the Li-Cor 200, Huskeflux LP02, Kipp & Zonen CMP3, and Eppley 8-48.

Of the four sensors evaluated the Eppley black and white pyranometer (model 8-48) is considered the industry standard for solar radiation measurement. While it is significantly more costly than many of the alternative sensors, it also has a reputation for durability and reliability over time.

The Li-Cor 200 pyranometer is also very popular for incident solar measurement, probably due to its very reasonable cost. However, durability of these sensors is relatively low, and it might even be considered as a disposable sensor because of the need to replace them at a 1-2 year frequency.

Another important factor in selecting pyranometers is calibration requirements. Most of these instruments will need to be returned to their manufacturer for re-calibration approximately every two years. For this reason, spare sensors should be kept on-hand to replace sensors that must be sent away for re-calibration. This will add significant cost if a high-end pyranometer is selected for use at the HIPPNet plot sites.

Make	Model	Type	Measurement Range	Sensitivity	Approx. Cost	Cable Cost	Accessories
Li-Cor	LI-200SL	Silicon photvoltain detector	400 - 1100 nm	90 μA/1000 Wm^2	$260	3m cable incl. (+$15 for 15m cable)	2003S mounting/leveling fixture ($47), CM 225 solar stand ($31)
Huskeflux	LP02	blackened thermopile	305 - 2800 nm	15 μV/Wm^2	$800	5 m cable incl.	CM 225 solar stand ($31)
Kipp & Zonen	CMP3	blackened thermopile	310 - 2800 nm	5-15 μV/Wm^2	$980	10 m cable incl.	CM 225 solar stand ($31)
Eppley	8-48	differential thermopile	285 - 2800 nm	10 μV/Wm^2	$1,575	$1.00/ft	mount incl.

Recommendations from Tom Giambelluca

Many of these recommendations have already been integrated into the body of the report.

- I strongly recommend going with Campbell. We have long experience with them and other vendors. They have the most complete and well-integrated sensor-logger-data transmission array available.
- Your stations can be adequately run using Campbell CR1000 loggers: $1350 each
- Data transmission options will depend on the sites. Radio, digital mobile phone, and satellite transmission options are possible.
- soil moisture at 5 cm and 20 cm
  - CS616 water content reflectometers: $150 each plus $0.68/ft for the cable
- soil temp (at 2 depths)
  - TCAV averaging soil thermocouples: $160 each plus $0.74/ft for the cable
- air temp and relative humidity: Vaisala HMP45C temperature/humidity probes
  - $525 each plus $180 for radiation shield and $0.55/ft for the cable
- wind speed and direction
  - 05106 RM Young wind monitor, marine quality: $1095 plus $0.55/ft for the cable; also need mounting hardware that depends on the tower construction
  - Note that cheaper sensors are available, but I highly recommend spending bit more to avoid frequenct costly repairs down the road.
- PAR (photosynthically active radiation)
  - LI190SB quatum sensor: $515 plus $60 for the leveling base and $0.28/ft for the cable
- fuel moisture
  - DMM600 Duff moisture meter: $1625
- precipitation
  - TE525 tipping bucket raingage: $330 plus $0.28/ft for the cable
- net radiation. There are two options:
  - REBS *Q7.1 net radiometer: $1150 plus $0.24 for the cable. The REBS instrument requires frequent desiccant changes and replacement of the wind shields.
  - Kipp and Zonen CNR1 net radiometer: $5000 plus $1.22/ft for the cable. If you have the funds, the Kipp and Zonen provides a lot more information (all four components of the of the net radiation--shortwave and longwave, upward and downward for both--) and they require less maintenance.

Note: Jim Juvik recommends also measuring soil heat flux for energy balance studies.

- Rainfall collection (for rainfall chemistry samples)
    - Contact Martha Scholl (USGS, Reston), who has used buckets with mineral oil to stop evaporative loss.

- wet and dry deposition (of, for example, nutrients from the atmosphere).
    - Barry Huebert (UHM, Oceanography) has a couple of these and has offered to transfer them to me.

- throughfall
    - We use a trough-type gauge with a large tipping bucket. This instrument is of our design and we have them made in Thailand (about $700 each plus $89 for a Hobo event logger)

- stemflow
    - We use the same tipping-bucket device as for TF. We attach collars to the tree stems and connect them to the collectors via tubing and/or pvc pipe.

- fog drip
    - There are fog gauges, but they don't tell you how much fog drip there is. If you have above-canopy precip, throughfall, stemflow, and an estimate of evaporation, you can derive cloud water interception. We do this at other sites.

- stream stage
    - You have to decide whether to install some kind of channel control structure (weir or flume). This would require a difficult approval process. With the structure, you would construct a stilling well and a shelter for the logger. You then have to record water level behind the structure using either a pressure transducer (around $700) or a bubbler device (not sure of the cost). You also need a logger and power supply. Without the structure, you can record water level in a natural channel, if suitable. In either case, a rating curve must be developed relating water level to discharge. This requires a velocity meter (a good one costs around $3600).

- solar radiation
    - If you go with the Kipp and Zonen net radiometer, then this is already taken care of. If not, I recommend an Eppley 8-48 pyranometer (around $1600 last time I checked).

- Tower costs:
    - Of course this is highly dependent on the canopy height and the remoteness of the site. It can range from a few hundred dollars to many tens of thousands. You have to be able to climb the tower to install, level, and maintain the sensors. Having people climbing it requires a pretty substantial structure. We've been buying used triangular-base radio tower. The costs has been reasonable for the tower itself--serveral hundred for each 10-ft section as I recall. But the real costs are in the base and guy anchors, which can require tons of concrete (literally). For our 60-ft tower at Ola'a, we used 15000 lbs of concrete for the guy anchors. That's a lot of helicopter loads.

- **Measuring in clearings**
    - Minimum clearing size depends on the height of the vegetation. For precipitation, recommendations for the minimum distance to an upwind obstacle range from 2 to 4 times the height of the obstacle above the raingage. So, in tall trees, you'd have to have a pretty big clearing. You can put a raingage on a non-climbable mast in a smaller clearing, to get it up high enough to meet the requirements. For wind speed, clearings are really no good unless they are huge. Temperature and humidity, you can get reasonable numbers in a fairly small clearing--this really depends on what you want to use the data for. If fine-scale differences between air temperature and canopy temperature are needed, for example, then obviously the air temperature in the clearing is not very helpful. If you just want to characterize the area, then it's probably okay.

- **Soil Heat Flux**
    - Jim Juvik is correct, soil heat flux is necessary, especially for open canopy locations. We generally use four HFT3 soil heat flux probes and two TCAV soil temperature sensors per site for this purpose. The HFTs are installed at 8 cm. The TCAV probes both have to be installed in the upper 8 cm layer. So if you want soil temperature at two depths (as previously indicated), you will need 3 TCAVs. Also, with the added sensors, the CR1000 logger may not be adequate. You might have to move up to a CR3000 ($2800), or add a multiplexer, e.g. AM16/32 ($560). The sensor costs are:

      HFT3: $365 each plus $0.24/ft for the cable
      TCAV: $160 each plus $0.74/ft for the cable